Modeling Effects on Strain and Strain Rate Histories in Automotive Impact

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Outline

- Strain rate effects in crash of steel structures
  - Consequences of modeling approaches on crash simulations
- Modeling effects on strain rate calculations
  - Simple tension
  - Symmetric crush
  - Un-symmetric crush
- Conclusions

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Strain Rate Effects and FEM

- For *coarse* FEM mesh discretization where mesh cannot conform to physical deformation, addition of strain rate sensitivity can be 'detrimental '
  - Models are already too stiff because of coarse meshes
- For *fine* FEM mesh discretization, incorporation of strain rate is necessary
  - 'Quasi-static' material models soften with increase in mesh density
  - Strain rate effect counters softening and localization
- Calculated strain rates are affected by
  - Element formulation and discretization
  - Strain rate model details

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Modeling of Strain Rate Sensitivity

- Experiments
  - Range of rates to test
  - Interpretation of experimental data

- Modeling
  - Constitutive models to fit experimental data
  - Range and history of strain rates during simulation

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Material Models for Strain Rate Sensitivity

- Empirical models
  - Function fit to empirical data
- Rheological models
  - Combination of rheological devices
- Micromechanical models
  - Based on dislocation mechanics

- Empirical, tabulated form is used in this study
  - Strain rate - plastic strain - stress

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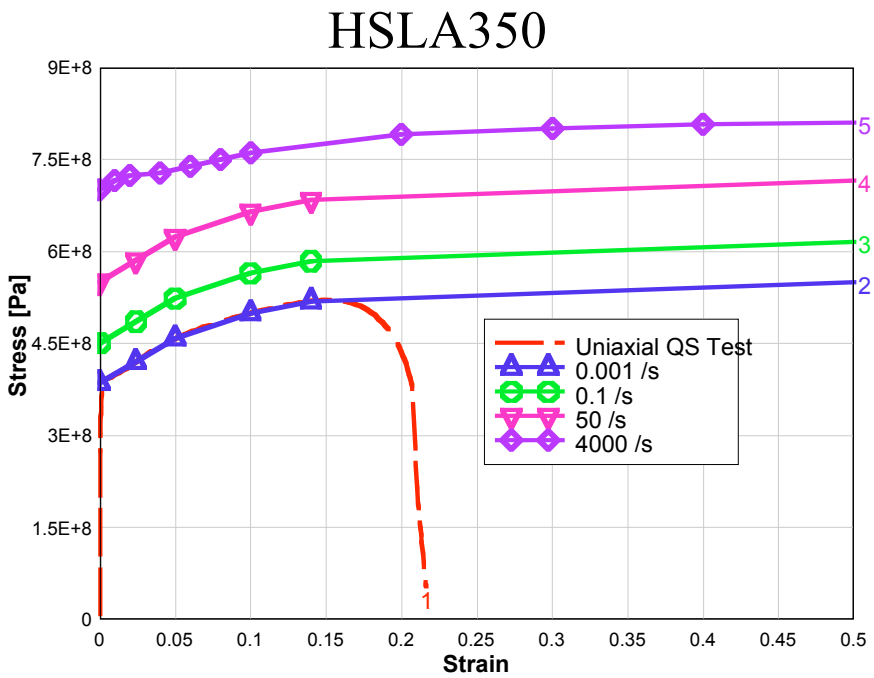
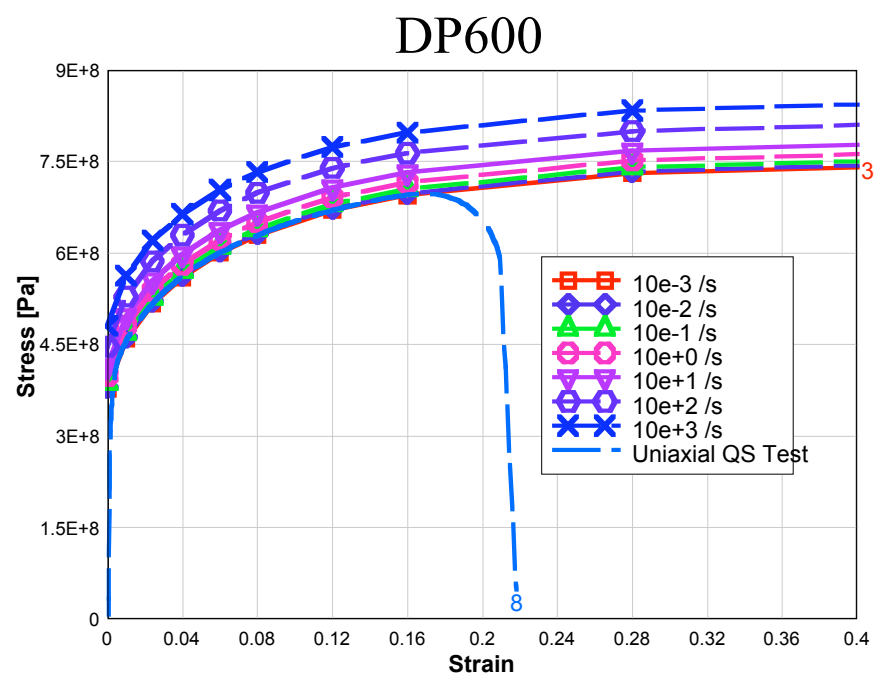
Examples of HSS Material Models





- Material data from servo-hydraulic and SHPB tests
  - Constant strain rate tests
- HSLA350 experimental data shows pronounced transients but they have been disregarded here

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Strain Rate History

- In explicit time integration strain rates are computed at every *computational* time increment, Δt_{calc}
  - Δt_{calc} ~ element size ~ *micro*second
- Simulation results are saved approximately every *milli*second or more, Δt_{save}
- Strain rates in post processing software are calculated by differentiation of strains saved at intervals Δt_{save}
  - Reported strain rates are underestimated

- New program was developed to extract and analyze strain rates at Δt_{calc} without saving states every Δt_{calc}

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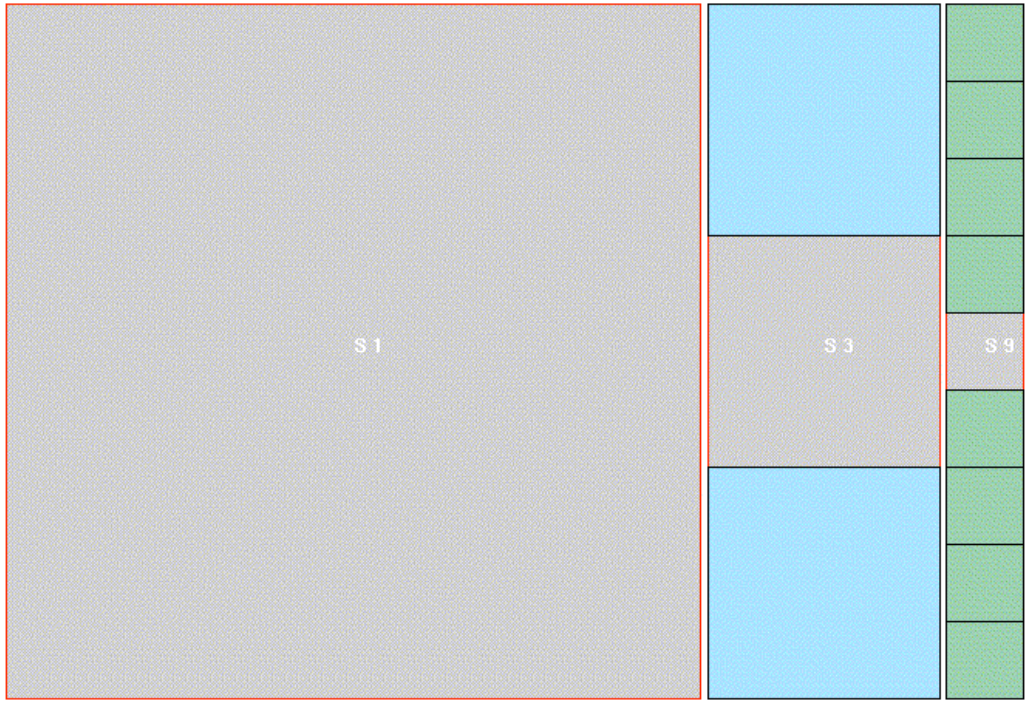
Uniaxial Tension Test Problem



- Each strip is pulled in vertical direction to produce constant *total* strain rate of 100/s
- Material models are based on either *total* or *plastic* strain rate
  - Plastic strain and strain rate histories are investigated

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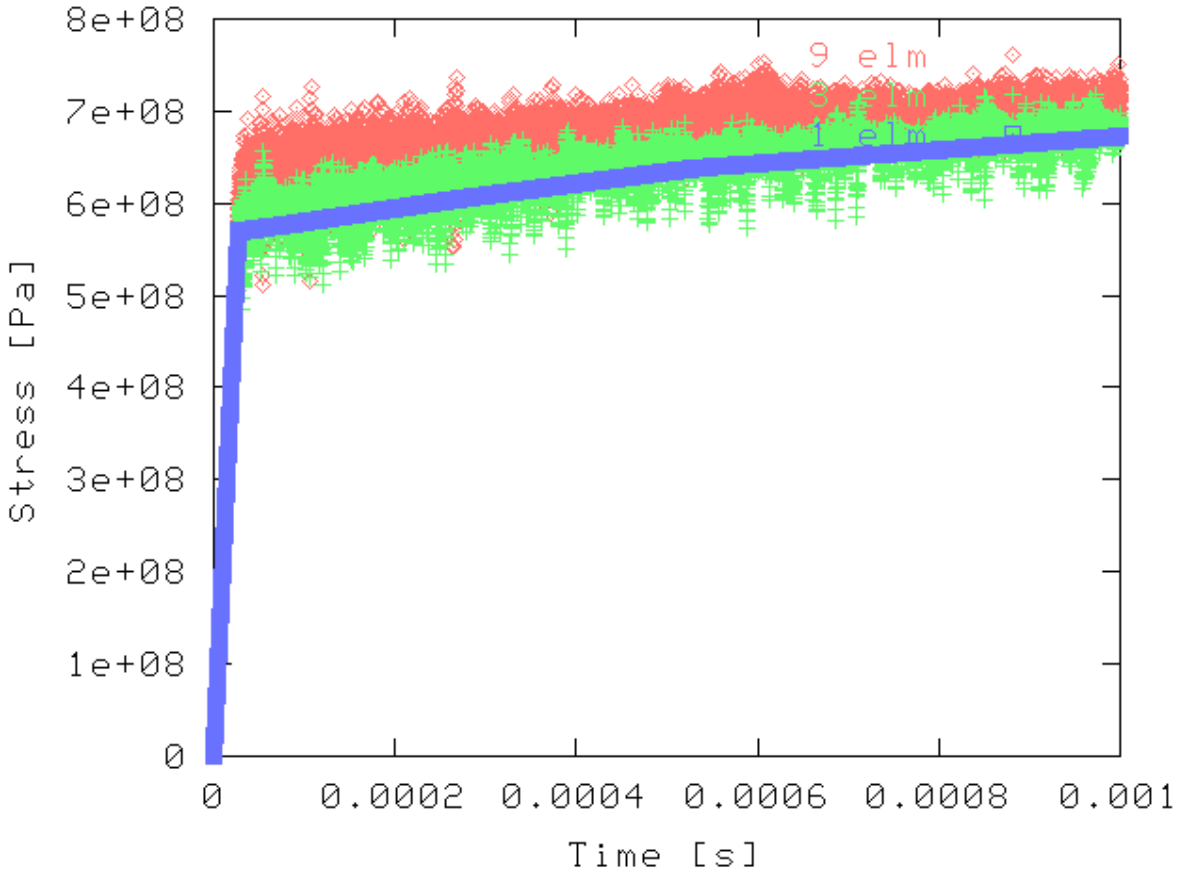
Model Based on *Total* Strain Rate: Stress History



Red - Small element

Green - Medium

Blue - Large

- Oscillations increase with element density
- Stress oscillations introduce *additional* noise in the acceleration trace

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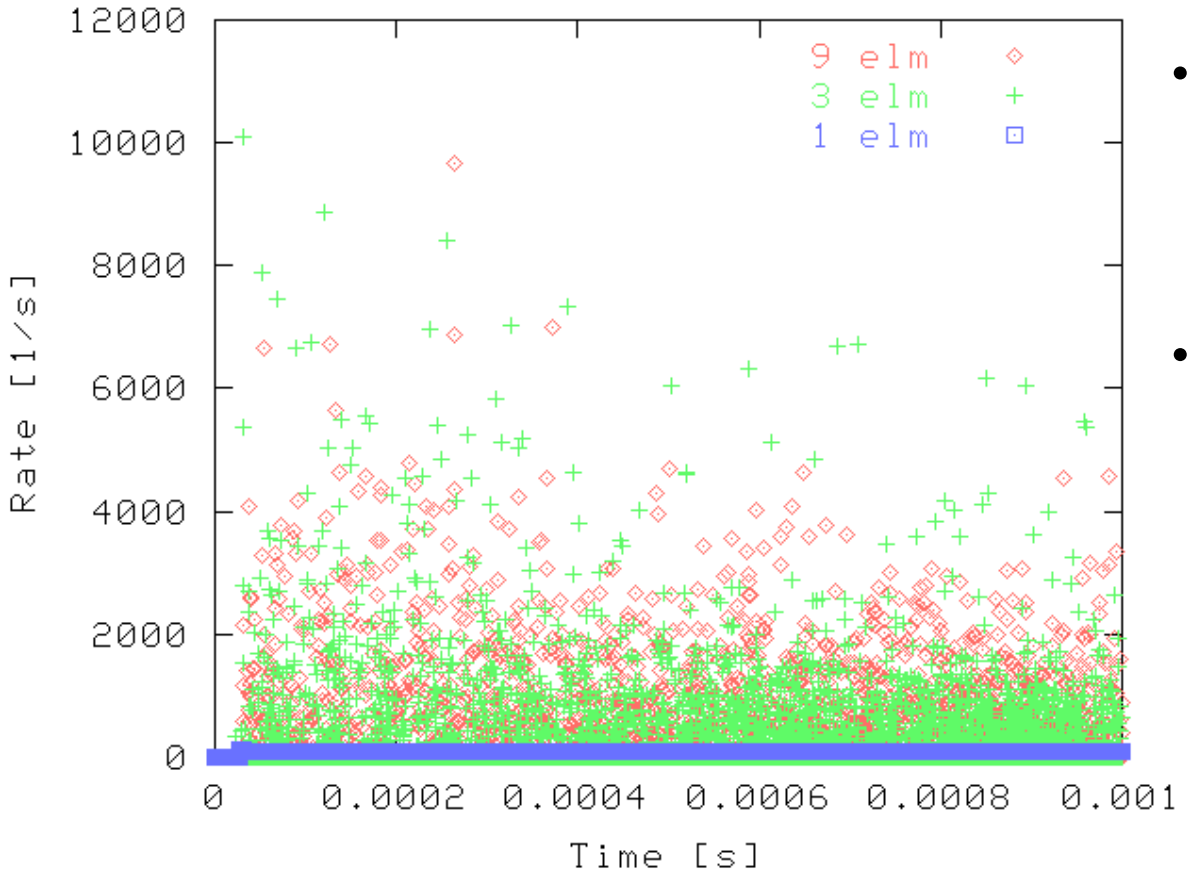
Model Based on *Total* Strain Rate: Rate History



- Maximum rates are well above imposed homogenous rate
- It is important how plastic strain:strain-rate evolves

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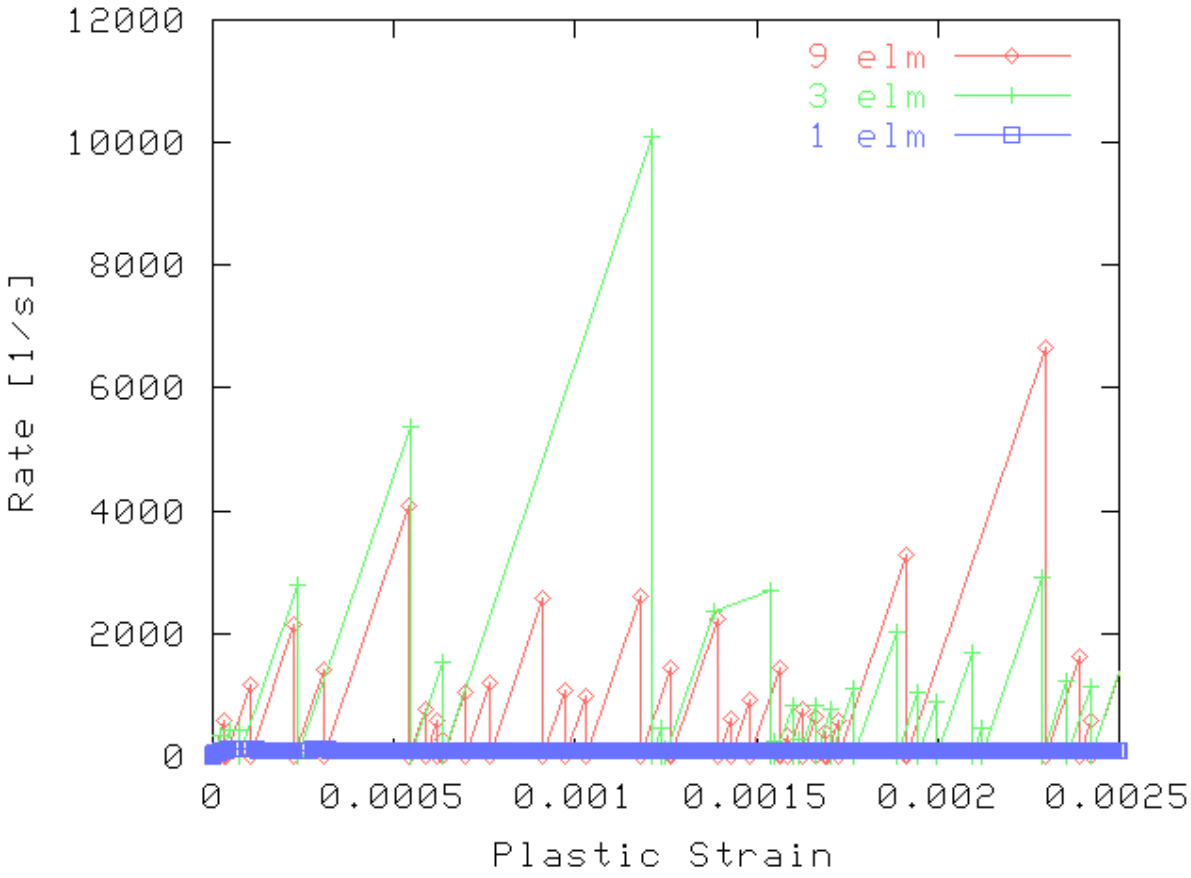
Model Based on *Total* Strain Rate: Plastic Strain Evolution



- Plastic deformation occurs in jumps that catch up to the imposed homogenous deformation
- Plastic strain rate is mostly zero except at distinct times where rate burst occurs

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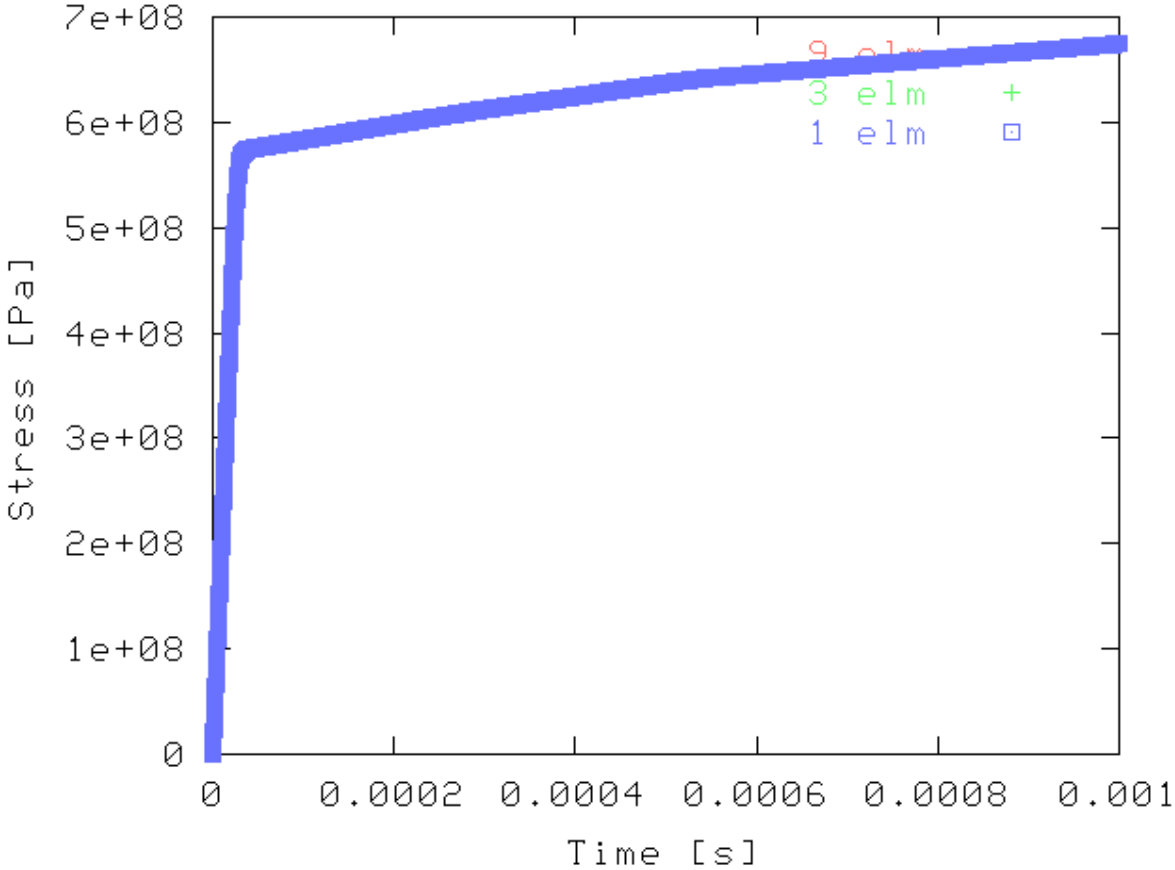
Model Based on *Plastic* Strain Rate: Stress History



- All stress histories fall onto the same curve
- Same happens for material model *without* strain rate sensitivity

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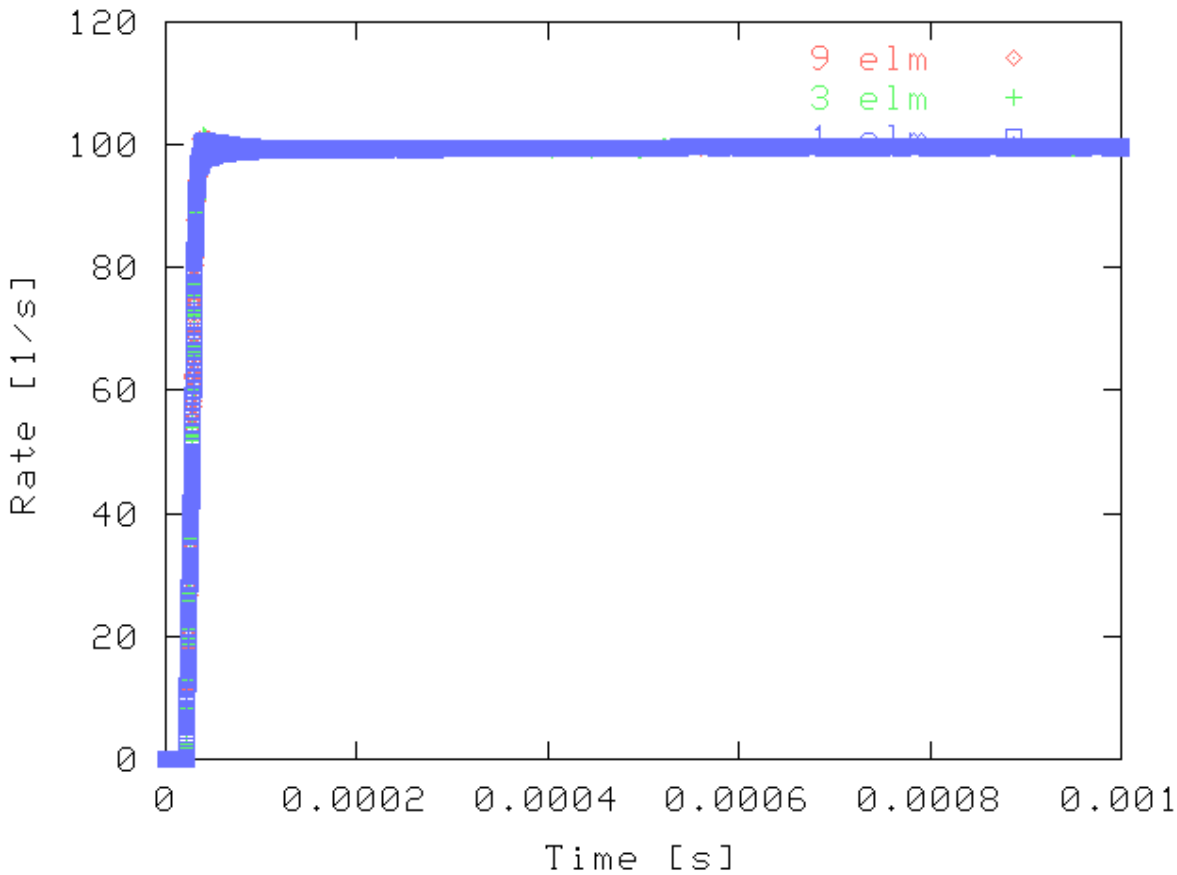
Model Based on *Plastic* Strain Rate: Rate History



- Plastic strain rates equal imposed homogenous rate

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Element Discretization Effects in Simple Tension

- Models based on **total** strain rate
  - Mesh refinement increases stress and rate oscillations
  - Plastic strain occurs in jumps to catch up the strain in the homogeneous deformation
  - Average strain rate in an element ~ 0 (by median method)

- Models based on **plastic** strain rate
  - Rate and stress histories do not change with discretization
  - Same trends as in strain rate insensitive models
  - The deformation is very homogeneous even for material with strain softening
  - Good and bad news

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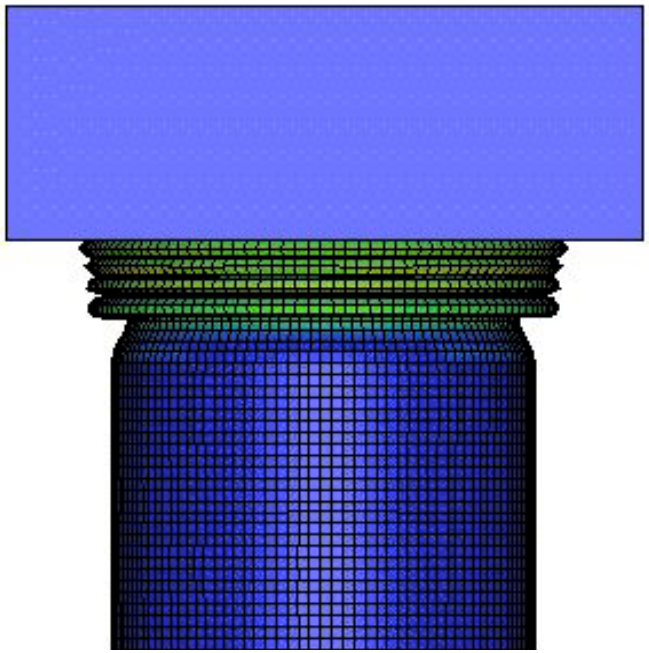
Axi-symmetric Tube Crush

- Configuration adopted from literature
  - Abramowicz, W. and Jones, N., Dynamic Axial Crushing of Circular Tubes, Int. J. of Impact Eng., vol. 2, no. 3, p. 263-281, 1984.
- DQSK steel tubes
- Results
  - Effect of mesh density
  - Effect of strain rate model formulation



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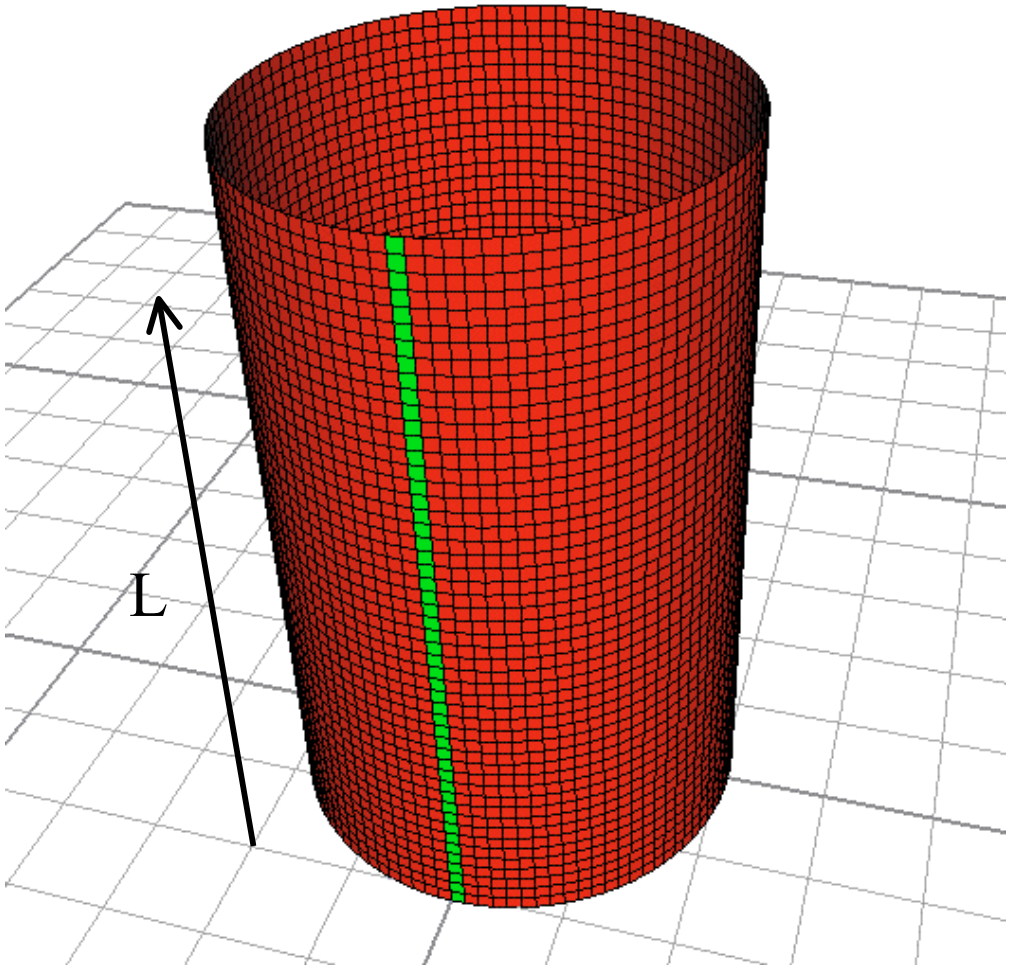
Axi-symmetric Tube Crush Model



- Green patch denotes modeled tube segment
- Axi-symmetric model

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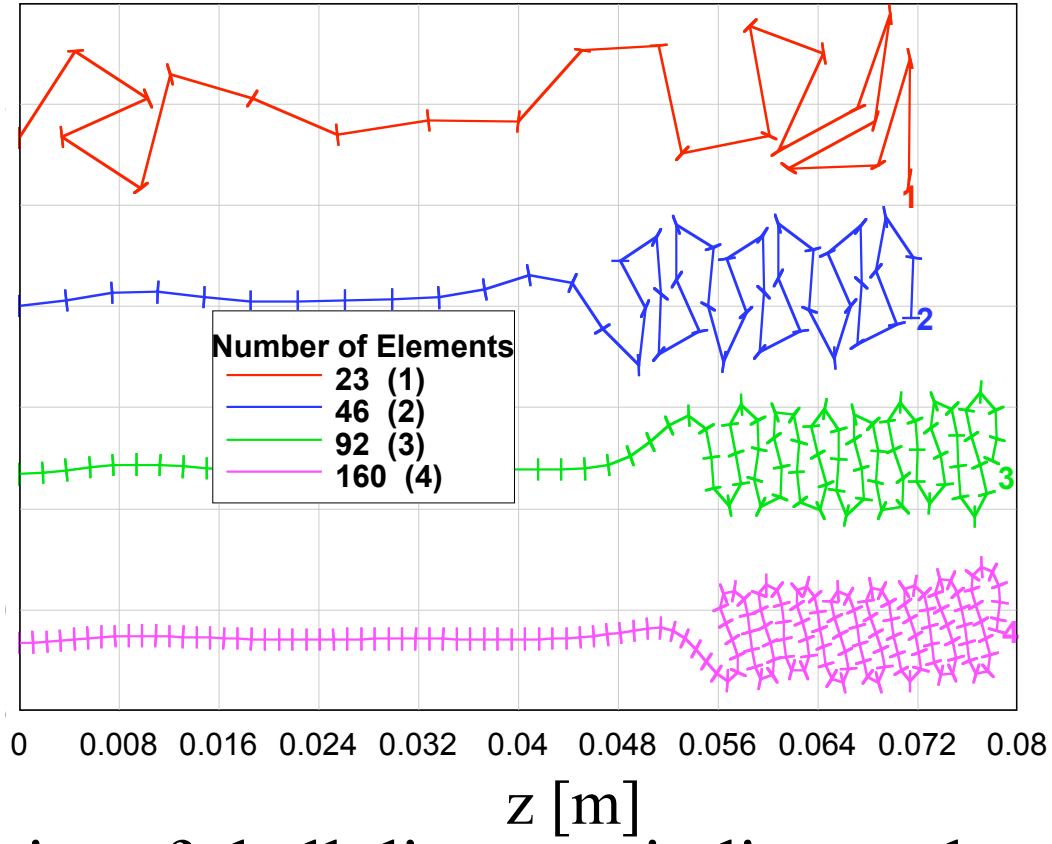
Effect of Element Discretization on Deformation



- Continuity of shell directors indicates the quality of the model

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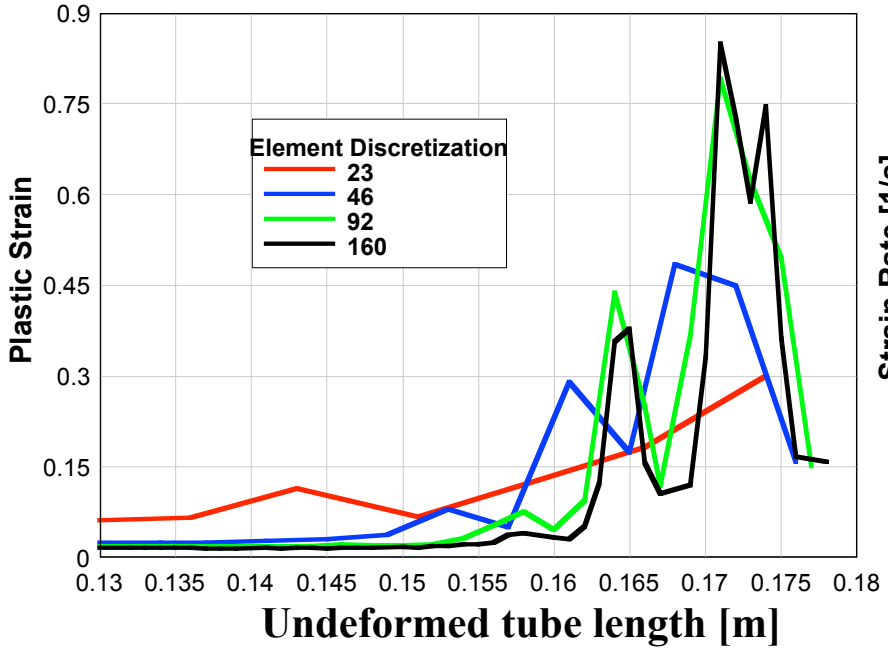
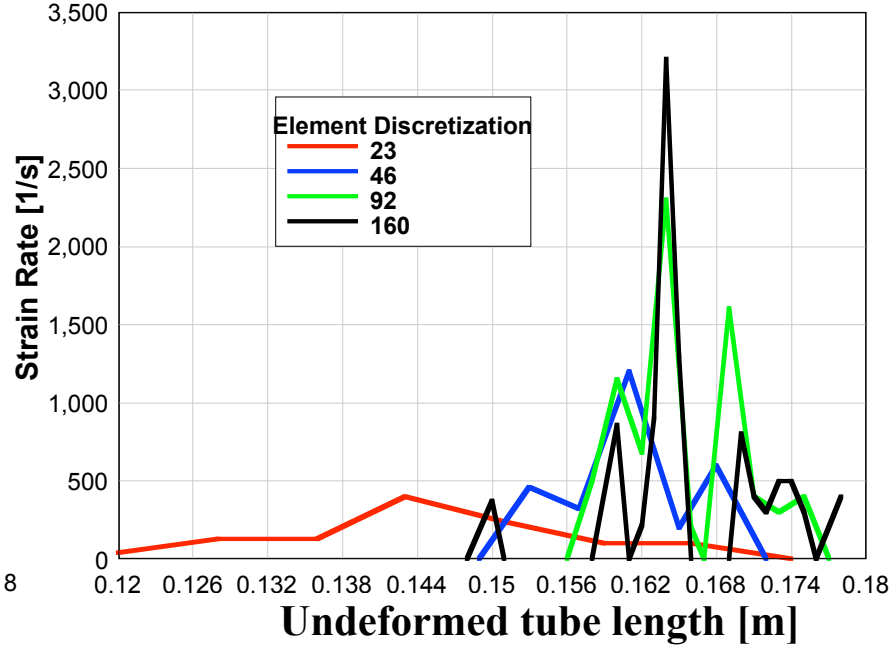
Distribution of Plastic Strains and Strain Rates





- Strain and rate distributions at the time of formation of the second fold
- Strain rate distribution narrows with increased discretization

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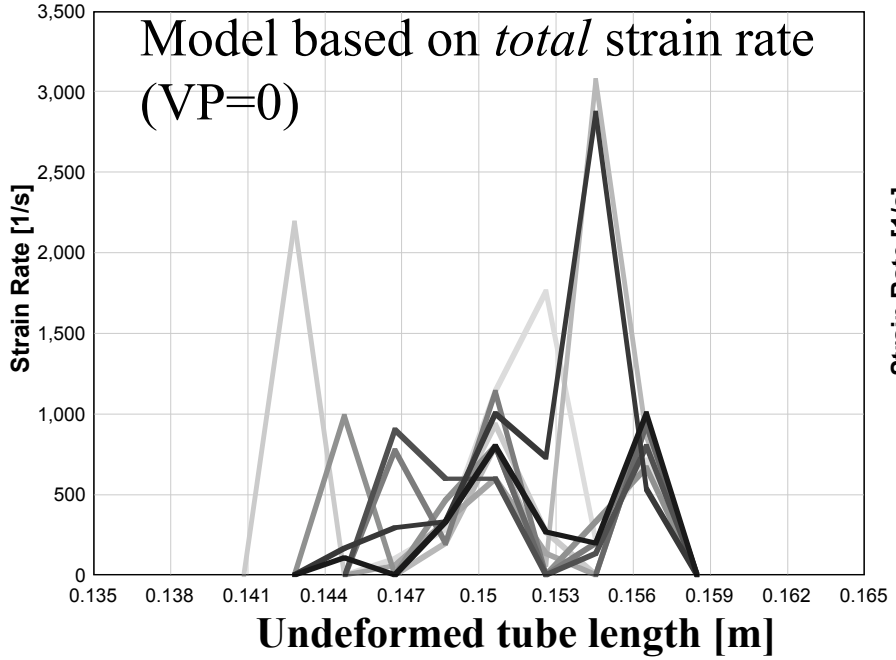
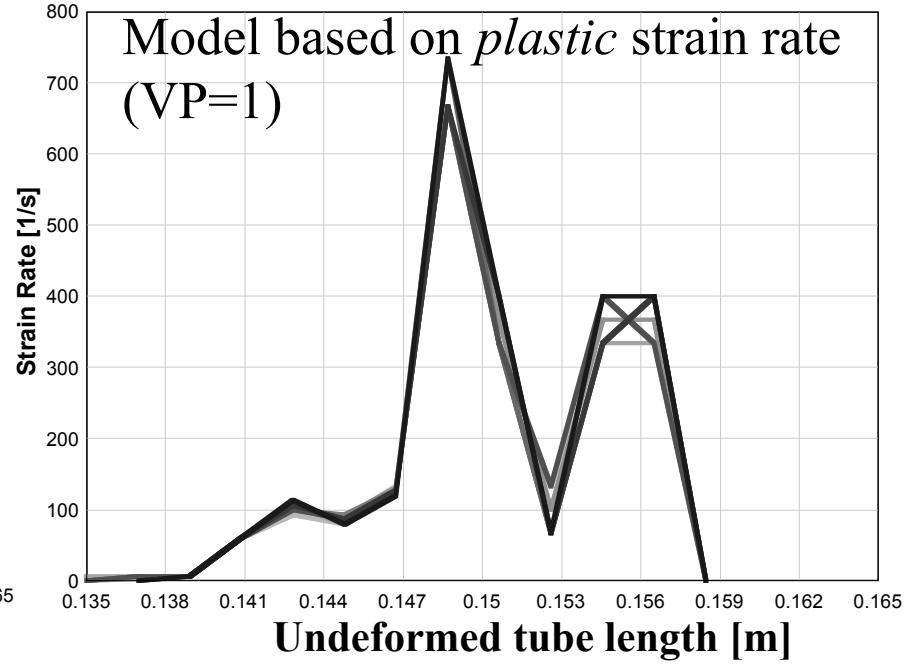
History of Strain Rates





- Curves of strain rate distributions that are 5 computational increments apart (Shade of grey denotes time sequence)
- Strain rate history for VP=1 appears more reasonable

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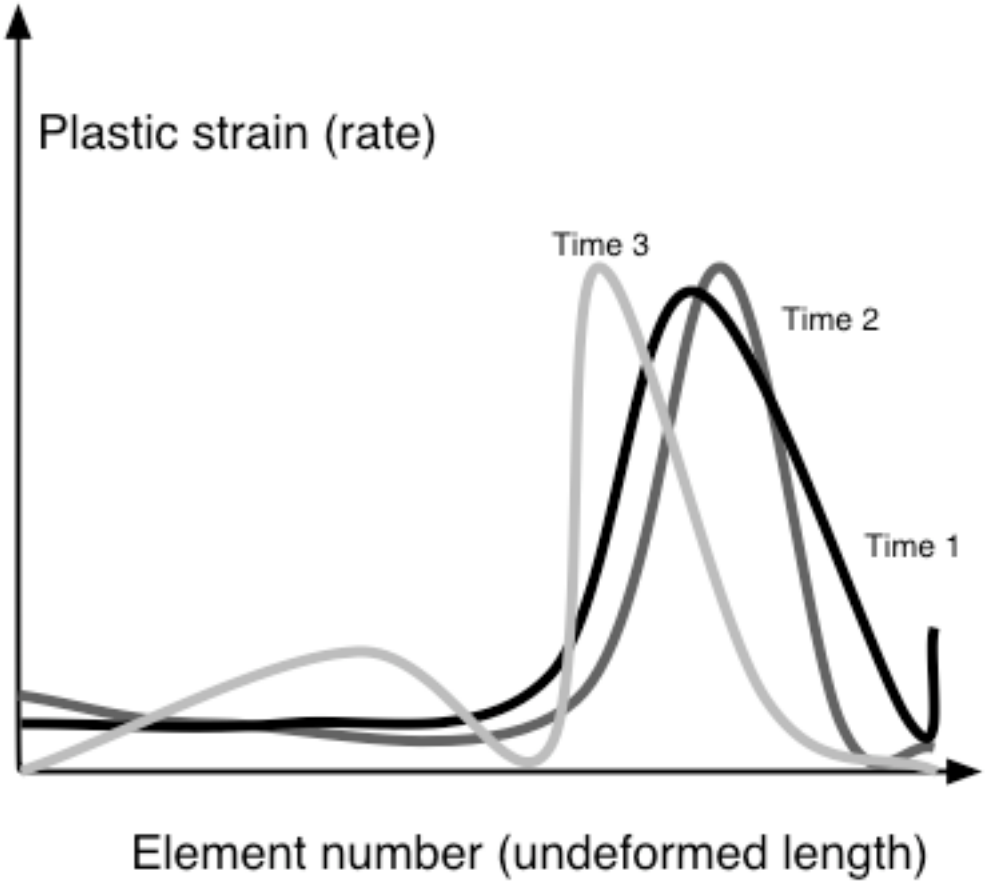
History of Plastic Strain and Plastic Strain Rates



- Each frame contains 10 curves representing plastic strain rate distributions for 10 consecutive *computational* time increments
- Frames are linked to develop animation of plastic strain rate distribution

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Plastic Strain Rate History Animations

- Coarse mesh, model based on *total* strain rate
- Fine mesh, model based on *total* strain rate
- Fine mesh, model based on *plastic* strain rate

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Modeling of Axi-Symmetric Crush - Review

- **The Effect of Mesh Resolution:**
  - Rates increase with mesh density down to size where shell element theory is at its limits
  - With an increase in mesh density, strain rate magnitudes increase, and the active strain rate zone decreases
  - ***Implication is that the mesh resolution and the material model are not independent***

- **The Effect of Element Formulation:**
  - No marked difference in element formulations
  - All common element formulations are *good enough*

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Un-symmetric Crush

- Prevailing crush mode in automotive structures
- Finite elements warp, bend and stretch at angles to element sides
- What are the actually calculated plastic strain *rates* in *un-symmetric* crush and how do they vary with modeling options?

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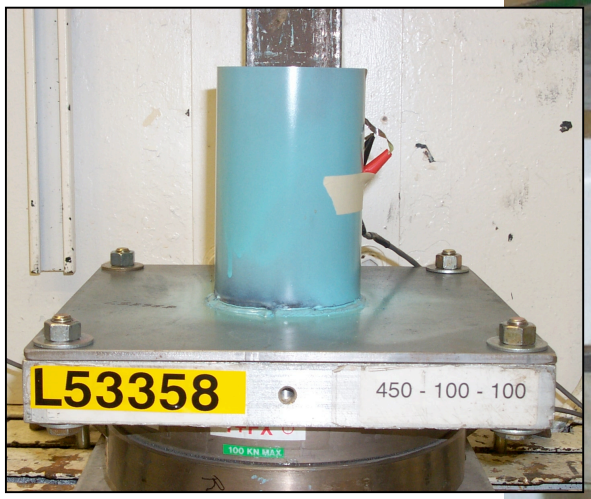
Drop Tower Test for HSLA350



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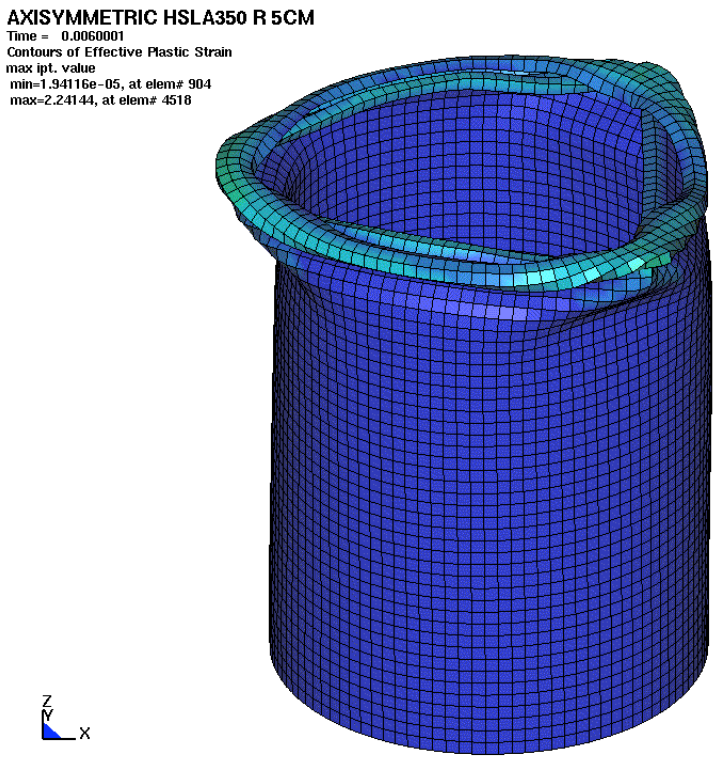
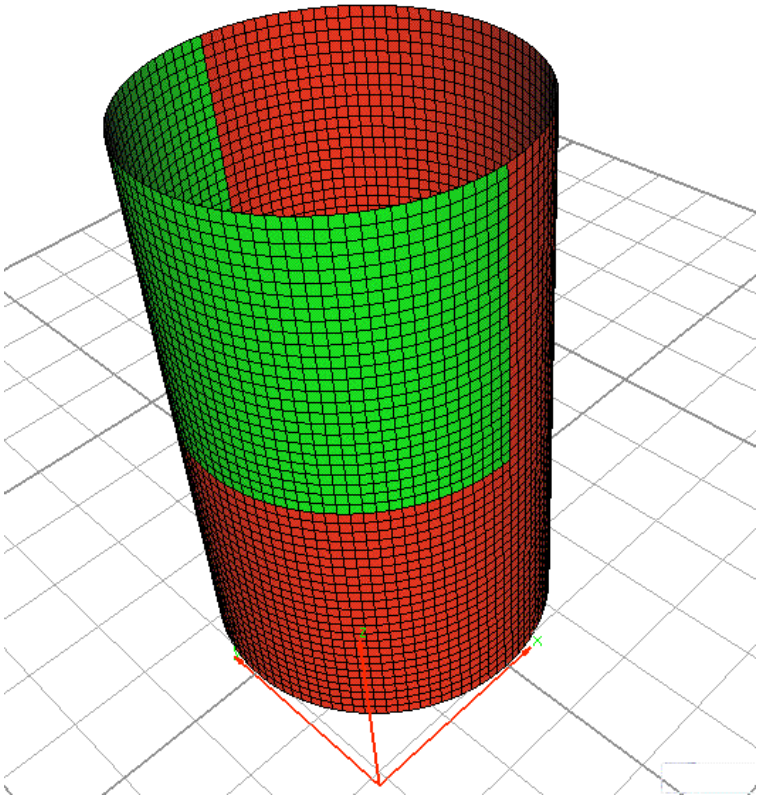
Elements Selected for Analysis





- Green patch denotes selected elements for strain rate history analysis

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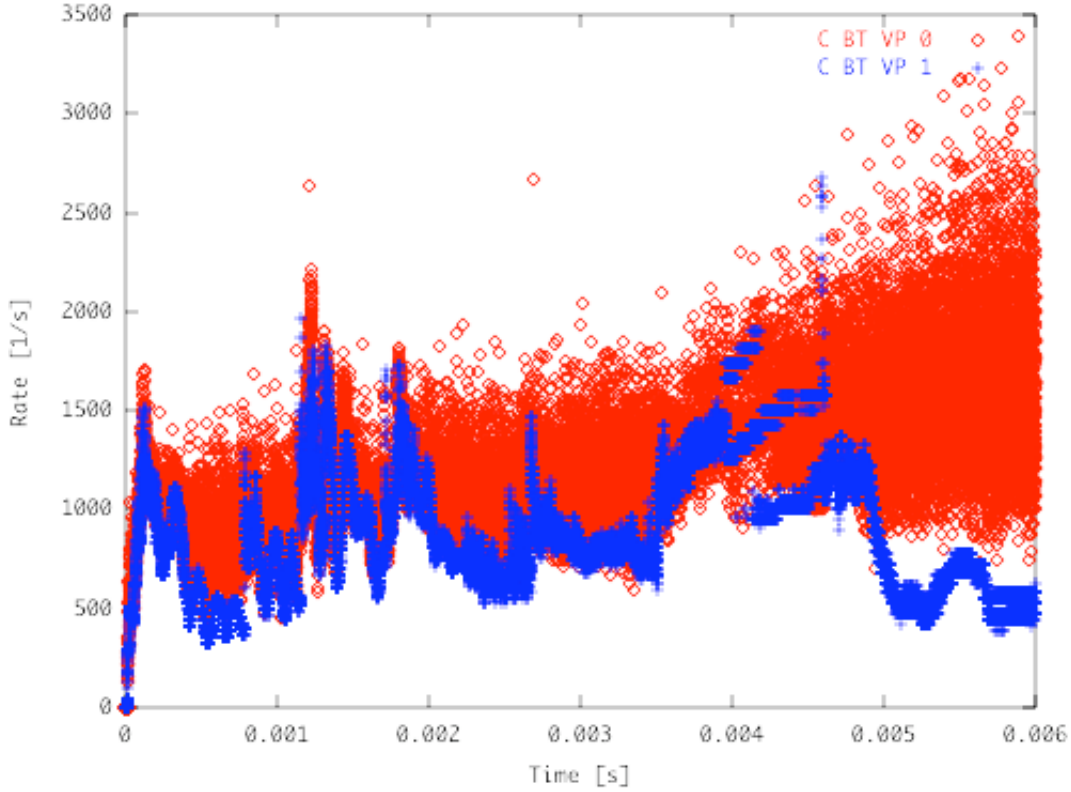
History of Maximum Rates, BT Shell



C: Coarse mesh

- L~2T

BT: Belytshko-Tsay shell element

VP: VP effect

- VP=0 model based on *total* strain rate
- VP=1 model based on *plastic* strain rate

- History of MAXIMUM strain rate is significantly more noisy for VP=0
- For VP=0 elements "pop" in and out of plastic straining between steps

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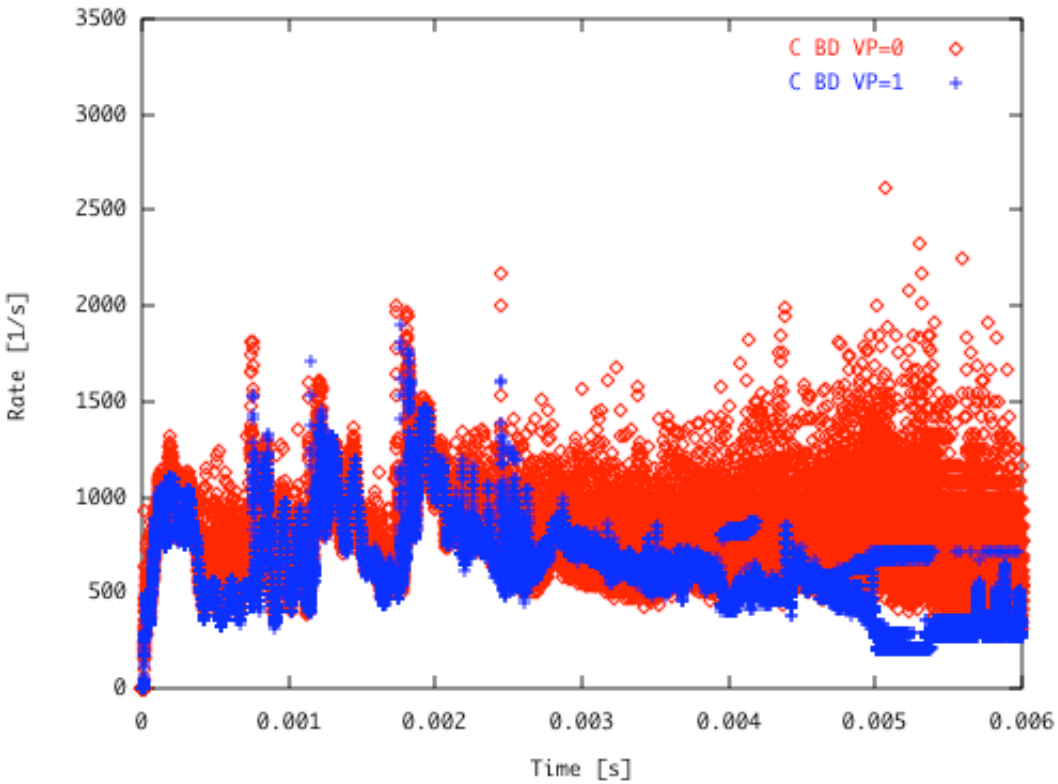
History of Maximum Rates, BD Shell



C: Coarse mesh

- L~2T

BD: Bathe-Dvorkin shell element

VP: VP effect

- VP=0 model based on *total* strain rate
- VP=1 model based on plastic strain rate

- VP effect the same as for the BT shell
- Strain rates are less noisy overall for BD shell

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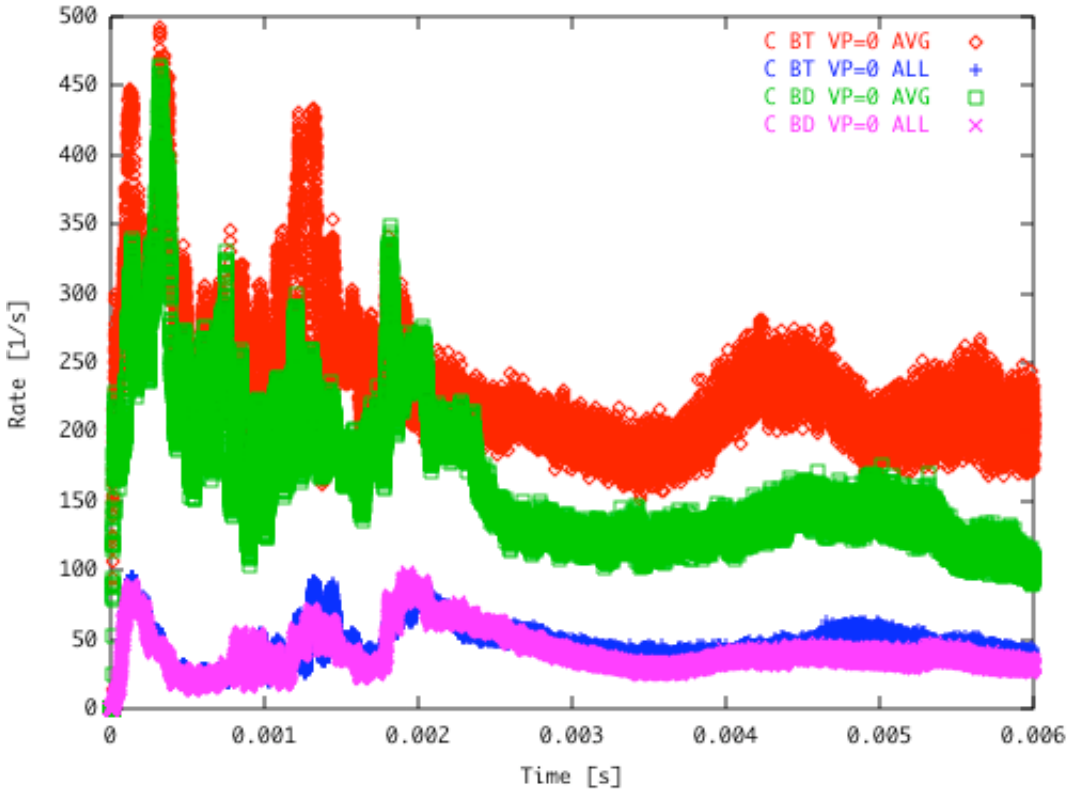
History of Average Rates, VP=0



AVG: Average over all elements for which plastic strain rate > 0

ALL: Average over all elements

VP=0: Model based on total strain rate

C: Coarse mesh

- Difference between ALL and AVG indicates spreading of plastic zones
- BD element tends to distribute strains more widely
  - Important because traveling of corners during fold formation and BT tends to slow and arrest them

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Plastic Strain Rate History Animations

- Coarse mesh, BD shell, VP=0
- Coarse mesh, BT shell, VP=0

- Coarse mesh, BD shell, VP=1
- Coarse mesh, BT shell, VP=1

- Fine mesh, BD shell, VP=0
- Fine mesh, BD shell, VP=1

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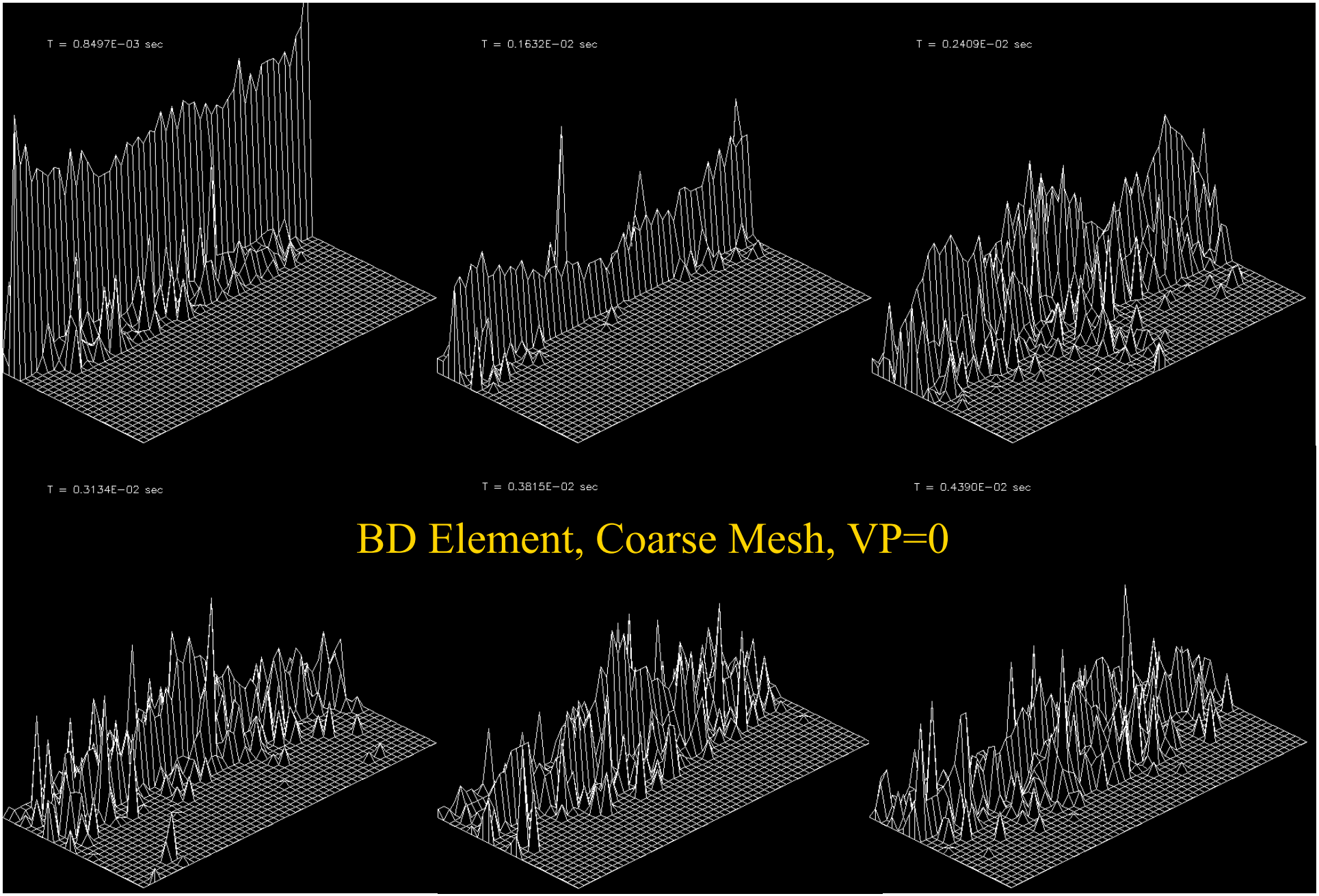

BD Element, Coarse Mesh, VP=0

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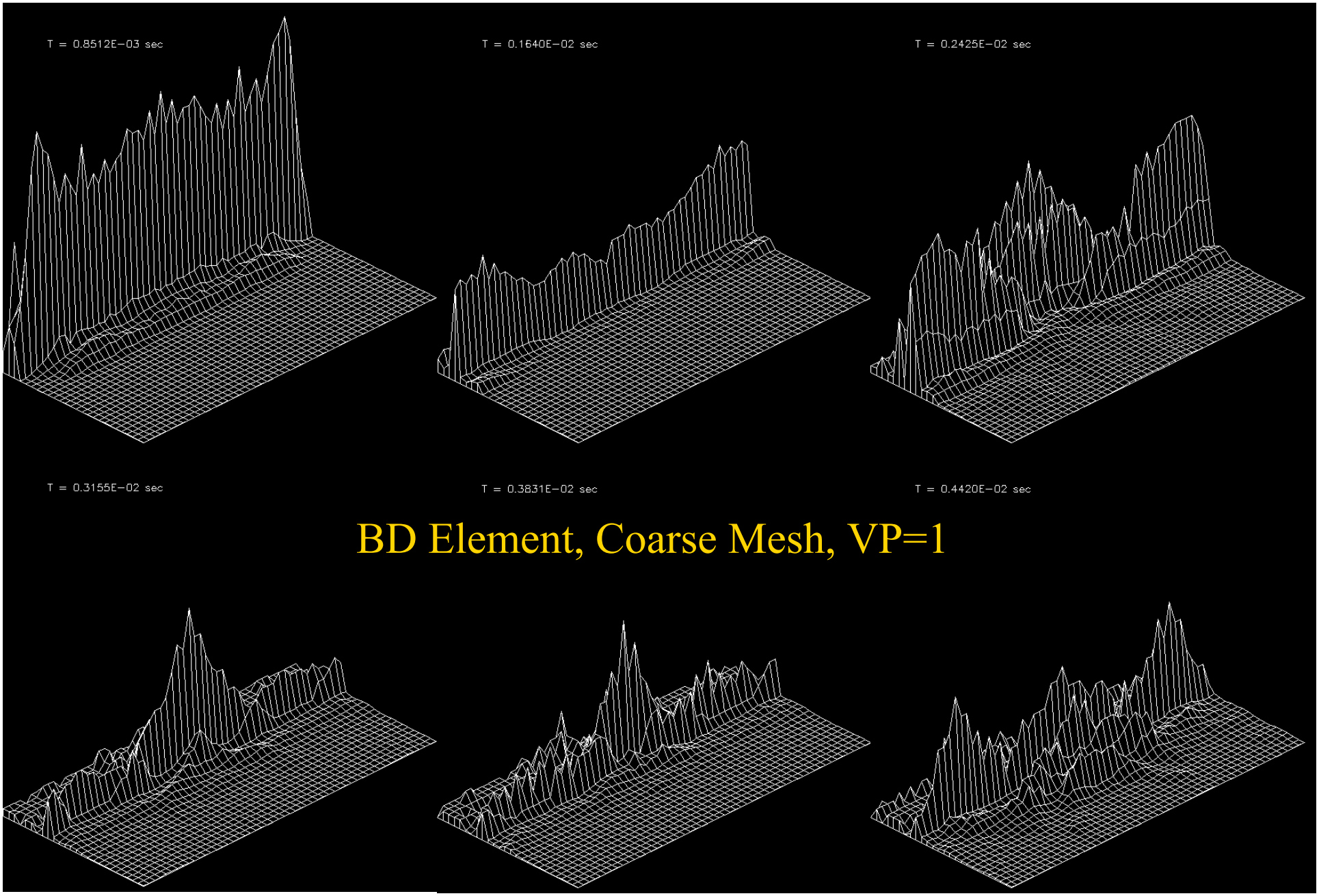

BD Element, Coarse Mesh, VP=1

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Conclusions

- We have determined ranges of calculated plastic strain rates for symmetric and un-symmetric crush characteristic of automotive impact situations
- For un-symmetric crush, *BD element* allows plastic corners to travel easier (delocalize plastic deformation)
- Models based on *plastic* strain rate tend to de-localize plastic deformation
  - Results in smooth history of plastic strain rates
  - Maximum plastic strain rates are lower
- For available element formulations, rate sensitivity cannot be decoupled from element discretization
  - Rates (stresses) increase with mesh resolution
  - Heuristics related to element size are necessary
  - The most significant effect is in early stages of impact

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